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ON THE NONMESONIC DECAY OF THE Λ IN NUCLEAR MATTER

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In the early studies of hypernuclei it was realized that Pauli Blocking would inhibit the $\Lambda\to\pi N$ decay in a heavy system[1] and that the dominant decay mode of heavy hypernuclei would be the nonmesonic decay corresponding to the reaction $\Lambda N\to NN$, in which the momentum of the final nucleons is about 420 MeV/c in the center-of-mass frame. While this expectation has been born out by experiment,[2] attempts to calculate the absolute nonmesonic decay rate have not been so successful. The most detailed attempt to include the effects of nuclear correlations on the decay rate, that of Adams,[3] gave a value of 0.06 for the ratio of the nonmesonic decay rate to the free decay rate, $\Gamma_{nm}/\Gamma_{free}$. We are aware of only one measurement of this ratio,[4] made in ^{16}O, which yielded a value of 3±1. While the statistics in the experiment were poor (there were 22 events) and the background problems were severe, we believe that the discrepancy should be subject to further theoretical and experimental investigation.[2]

As a first step towards the theoretical investigation, we have recalculated the pion exchange, or Karplus-Ruderman,[5] contribution considered by Adams; in addition, we have also considered the contribution from ρ exchange. The latter, in the limit of $m_\rho\to\infty$, becomes the contact interaction considered by Block and Dalitz.[6] We have, however, introduced correlations in a way that differs from that used by Adams; we simply multiply the uncorrelated wavefunction by a simple correlation function which we take to be the same in all two body spin-isospin states. In particular, in the results quoted here we have not yet introduced tensor correlations, which Adams found to suppress the nonmesonic decay rate by a factor of about 5.

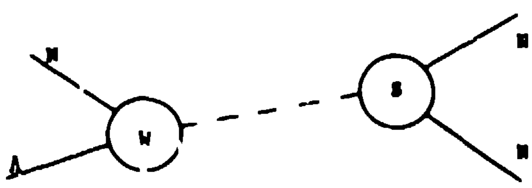

Fig. 1. π Exchange Contribution to $\Lambda n\to NN$.

The pion exchange potential can be calculated from the diagram in Fig. 1, where the $\Lambda\to N\pi$ decay vertex is known. Experimentally the Λ decays satisfy the $\Delta I=1/2$ rule quite well, so that we build this into our amplitude by writing it as

$$a(\Lambda\to N\pi^i) = G_F\mu^2 A\bar{N}\ (1+\lambda\gamma_5)\tau^i\Lambda \quad .$$

Here $A = 1.05$ and $\lambda = -6.87$ are empirical constants,[7] τ^i are the usual isospin matrices, N is the nucleon Dirac spinor-isospinor, and Λ is the direct product of the usual Dirac spinor for the Λ and the spurion isospinor $(0,1)^T$. We introduce a form factor $\Phi_\pi(k^2) = (\Lambda_\pi^2-\mu^2)/(\Lambda_\pi^2-k^2)$ with $\Lambda_\pi^2 \cong 20\mu^2$ to describe the strong interaction smearing of the πNN vertices,[8] and we take the nonrelativistic limit to obtain the π exchange $\Lambda N\to NN$ transition potential as

$$V_\pi = \frac{1}{3}\ V_s(r)\ (\vec{\sigma}_1\cdot\vec{\sigma}_2)\ (\vec{\tau}_1\cdot\vec{\tau}_2) + V_p(r)\hat{r}\cdot\vec{\sigma}_1\vec{\tau}_1\cdot\vec{\tau}_2$$
$$+ V_d(r)\ [(\vec{\sigma}_1\cdot\hat{r})\ (\vec{\sigma}_2\cdot\hat{r}) - \frac{1}{3}\ \vec{\sigma}_1\cdot\vec{\sigma}_2]$$

where the radial potentials are given by

$$V_s(r) = i\ \frac{Af}{\mu}\ \frac{\lambda}{2m}\ \frac{1}{2\pi^2}\ W_{0,2}\ (r,\mu)$$

$$V_p(r) = -\frac{Af}{\mu}\ \frac{1}{2\pi^2}\ W_{1,1}\ (r,\mu)$$

$$V_d(r) = -i\ \frac{Af}{\mu}\ \frac{\lambda}{2m}\ \frac{1}{2\pi^2}\ W_{2,2}\ (r,\mu)$$

and

$$W_{m,\ell}(r,\mu) = \int_0^\infty k^{2+m}\, dk\, \frac{j_\ell(kr)}{k^2+\mu^2}\ \Phi(r) \quad .$$

For $\Phi=1$ ($\Lambda_\pi\to\infty$), $W_{0,2}$ is divergent. This divergence represents a delta function potential at the origin which can be discarded when taking matrix elements between correlated wave-functions, and in any case no longer exists for $\Lambda_\pi\neq\infty$. Disregarding the divergence, for $\Phi=1$ $W_{2,0} = -\mu^3 k_0(\mu r)$, $W_{1,1} = \mu^2 k_1(\mu r)$, and $W_{2,2} = \mu^3 k_2(\mu r)$, where $k_\ell(\kappa) = \sqrt{\pi/2\kappa}K_{\ell+\frac{1}{2}}(\kappa)$ is the spherical Bessel function of the third kind.[9] For the π exchange potential alone we can write the nonmesonic decay rate, assuming that the correlation function is state independent, as

$$\Gamma_{nm} = \frac{mQ\rho}{\pi^3}\quad (G_F fA)^2\ \{\frac{3}{2}\ (\frac{\lambda\mu}{2m})^2\ \left|F_{00}\right|^2 + \frac{9}{2}\ \left|F_{10}\right|^2 + 6\ (\frac{\lambda\mu}{2m}\ )^2\ \left|F_{20}\right|^2\}$$

where Q is the momentum in the cm of the final nucleons, ρ is the density of nuclear matter, f is the pseudovector πNN coupling constant ($f^2/4\pi \cong 0.08$), and in the case that $\Phi=1$

$$F_{\ell 0} = \mu^3\ \int_0^\infty r^2 dr\ \ j_\ell(Q_r)\ j_0(\bar{k}r)\ k_\ell(\mu r)\ f(r)$$

where $\bar{k}$ is an average relative momentum of the Λ and N in nuclear matter and f(r) is the correlation function. The assumption has been made that $\vec{k}$ is sufficiently small that the reaction $\Lambda N \to NN$ takes place only from initial s states. Using the standard expression for the total lifetime of the free Λ particle[7] and the above parameters, we obtain

$$\left(\frac{\Gamma_{nm}}{\Gamma_{free}}\right)_\pi = 1.009 \; (0.388 \; |F_{00}|^2 + 4.500 \; |F_{10}|^2 + 1.551 \; |F_{20}|^2)$$

leading to the results of Table I. We emphasize two points: (i) the parity conserving s→d transition gives 80% of Γ_{nm}, by far the largest contribution; (ii) we consistently obtain larger results than Adams.[3]

Table I. $(\Gamma_{nm}/\Gamma_{free})$ From π Exchange

	s → s	s → p	s → d	total
no form factor no correlations	0.01	1.00	3.12	4.13
no form factor α = 2.0 fm^{-2}	0.003	0.54	1.95	2.49
no form factor α = 1.8 fm^{-2}	0.001	0.44	1.87	2.31
no form factor α = 1.0 fm^{-2}	2×10^{-4}	0.25	1.31	1.56
form factor $\Lambda_\pi^2 = 20\ \mu^2$ α = 1.8 fm^{-2}	0.031	0.005	1.03	1.06

The ρ exchange potential is dominated by the tensor-like $(\vec{\sigma}_1\times\vec{k})\cdot(\vec{\sigma}_2\times\vec{k})$ term, and we know that the s→d transition induced by this term gives the largest contribution to Γ_{nm}. To estimate the relative importance of the π and ρ exchange contributions, we make the approximation of retaining only the dominant term of the $\Lambda N \to NN$ transition potential of Fig. 2a. The difficulty in calculating this potential lies in estimating the strength of the $\Lambda N\rho$ vertex. We choose to estimate the $\Lambda p\rho^-$ vertex from the factorization approximation of Fig. 2b, omitting the $\sin\theta\cos\theta$ factor and obtaining the $\Lambda n\rho^0$ vertex by imposing the $\Delta I=1/2$ rule. It is known that this procedure is a good approximation to the magnitude but not the sign of the $\Lambda N\pi$ amplitudes.[7] More sophisticated estimates based upon $SU(6)_W$[10] or the quark model[11] could be made, but factorization will suffice for our purpose of estimating the importance of the ρ exchange contribution.

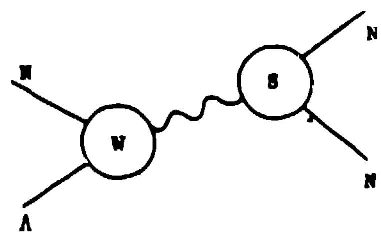

Fig. 2a. ρ exchange contribution to $\Lambda N \to NN$

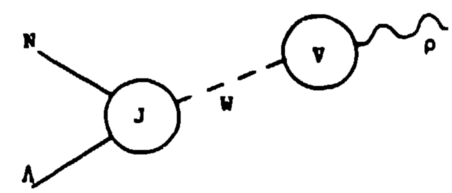

Fig. 2b. Factorization approximation to the weak $\Lambda N\rho$

Treating the vector mesons as a degenerate nonet, the tensor part of the $\Lambda N \to NN$ transition potential generated by ρ exchange is

$$V_{\rho d} = -\frac{G_F m_\rho^2}{4} \frac{(1+\kappa_\rho)(1+\kappa_\Lambda)}{2m^2} \frac{\sqrt{3}}{2\pi^2} W_{\rho d}(r) \left[(\vec{\sigma}_1\cdot\hat{r})(\vec{\sigma}_2\cdot\hat{r}) - \frac{1}{3}\vec{\sigma}_1\cdot\vec{\sigma}_2\right] \vec{\tau}_1\cdot\vec{\tau}_2$$

where κ_ρ and $\kappa_\Lambda = \kappa_\rho(1-\frac{2}{3}\alpha)$ are the magnetic type couplings at the strong and weak vertices, $\alpha = 0.6$ is related to the magnetic F/D ratio by $F/D = (1-\alpha)/\alpha$, and

$$W_{\rho d}(r) = \int_0^\infty k^4\, dk\, \frac{j_2(kr)}{k^2+m_\rho^2} \frac{m_\rho^2}{k^2+m_\rho^2} \Phi_\rho^2(k^2) \quad .$$

Here the potential has a dipole form because of the weak form factor for which we assume vector dominance. The choice of κ_ρ has been the subject of some controversy in the literature. Höhler and Pietarinen[12] gave $\kappa_\rho = 6.6$ and vector dominance of the electro-magnetic form factor gives $\kappa_\rho = 3.7$. The apparent discrepancy is resolved by noting that the larger value is obtained at $k^2 = m_\rho^2$, and the smaller is obtained at $k^2 = 0$. This indicates the importance of including the form factor $\Phi_\rho(\vec{k}^2) = (\Lambda_\rho^2-m_\rho^2)/(\vec{k}^2+\Lambda_\rho^2)$ to interpolate between these values. With this form factor one should use $\kappa_\rho = 6.6$ and $\Lambda_\rho^2 = 2.27 m_\rho^2$.

Including the ρ exchange contribution to the transition potential leads to

$$(\Gamma_{nm})_{\pi+\rho} = \frac{6mQ\rho G_F^2}{\pi^3} \left| \frac{Af\Lambda\mu}{2m} F_{20}^{(\pi)} - \frac{m_\rho^2\sqrt{3}}{2} \frac{(1+\kappa_\rho)(1+\kappa_\Lambda)}{(2m)^2} F_{20}^{(\rho)} \right|^2$$

where

$$F_{20}^{(\rho)} = \int_0^\infty r^2 dr\, j_2(Qr)\, j_0(\bar{k}r)\, W_{\rho d}(r) \quad .$$

Using this we obtain the results of Table II. In view of the difficulty one has in predicting the relative sign of the s and p wave π decays when using the factorization approximation, we give the results for both choices of the relative sign of the π and ρ terms. (Factorization applied to both terms predicts a negative relative sign. Factorization for the ρ term along with the empirical sign for λ suggests a positive relative sign.)

Table II. $(\Gamma_{nm}/\Gamma_{free})$ including π and ρ exchange ($s \to d$ transitions only).

	alone	alone	$\pi+\rho$	$\pi-\rho$
no form factor no correlations $\kappa_\rho = 3.7$	3.12	0.49	6.08	1.13
no form factor $\alpha = 1.8\ fm^{-2}$ $\kappa_\rho = 3.7$	1.86	0.26	3.52	0.72
no form factor $\alpha = 1.8\ fm^{-2}$ $\kappa_\rho = 6.6$	1.86	1.13	6.13	0.06
form factor $\alpha = 1.8\ fm^{-2}$ $\kappa_\rho = 6.6$	1.03	0.49	2.91	0.10
$\Lambda_\pi^2 = 20\ \mu^2,\ \Lambda_\rho^2 = 2.27\ m_\rho^2$				

We regard the final row of Table II as providing our current "best esimate" of the ratio $(\Gamma_{nm}/\Gamma_{free})$. The π exchange term and the ρ exchange term are of the same order of magnitude, neither by itself can give a value of the ratio significantly greater than 1; however, when they are added coherently, the ratio is 2.91. Whether this agreement between the calculated and experimental values of the ratio $(\Gamma_{nm}/\Gamma_{free})$ survives further work on each is a question for the future. Still, it is clear that investigation of the nonmesonic decay of heavy hypernuclei can provide information on the weak $\Lambda N\rho$ coupling which is difficult, if not impossible, to obtain by other means.

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